

1 CONTROLLED RELUCTANCE AC INDUCTION MOTOR

2 The invention relates generally to the field of
3 electric motors and specifically to an AC motor with
4 improved performance characteristics.

5 PRIOR ART

6 Many types of electric motors are known to the
7 industry. Typically, these known motors have certain
8 desirable characteristics such as high starting torque,
9 variable speed and/or high power density. Often, however, a
10 motor with desirable characteristics for a given application
11 has certain disadvantages or deficiencies. These
12 undesirable characteristics often include relatively high
13 cost, electrical circuit complexity, radio frequency or
14 electromagnetic interference, energy inefficiency, limited
15 reliability and/or comparatively short service life.

16 SUMMARY OF THE INVENTION

17 The invention provides an AC power operated electric
18 motor that exhibits desirable torque/speed characteristics
19 when operated in an open loop condition and is effectively
20 speed and/or torque controlled with relatively simple and
21 economical electrical circuitry. The motor has a stator
22 with field windings that are energized with alternating
23 current and that are arranged to induce an AC current in a
24 conductive loop on a rotor or armature. In various
25 configurations of the motor, the field windings comprise at
26 least two coils angularly displaced from one another around
27 the rotor axis. The positions of the windings in some
28 configurations represent physically or mechanically distinct
29 phases.

1 The AC stator field is caused to move about the axis of
2 the rotor and the induced AC field in the conductive loop
3 produces a torque on the rotor causing it to rotate in
4 synchronization with the field rotation. The rotation of
5 the stator field is produced by switching or appropriately
6 modulating AC power to successive angularly displaced field
7 coils.

8 The motor can be arranged with 2, 4, 6 or even a
9 greater number of even poles and with as many field winding
10 phases as suitable for a particular application. Motor
11 torque, and therefore power, is multiplied in proportion to
12 the number of poles provided in the motor. The motor has
13 open loop speed/torque characteristics approaching the
14 desirable ideal of constant horsepower. These
15 characteristics include high starting torque and high speed
16 at low load.

17 Importantly, the motor lends itself to relatively
18 simple and energy efficient speed control and/or torque
19 control. A standard speed control over a 10:1 ratio is
20 readily achieved. Rated torque can be achieved at zero
21 speed with proper circuitry and therefore the speed range
22 can be from zero to the maximum rated speed. Some of the
23 additional advantages of the motor include low stall
24 current, operation on simple square wave power without
25 difficulty with harmonics, and increased power and/or torque
26 for a given physical size motor as compared to conventional
27 induction motors, for example.

28 BRIEF DESCRIPTION OF THE DRAWINGS

29 FIG. 1 is a schematic perspective view of a motor
30 illustrating principles of the invention;

1 FIG. 2 is a generalized graph illustrating the
2 relationship of torque versus rotor deflection angle for
3 motors constructed in accordance with the invention;

4 FIG. 3 is a schematic perspective view of a motor
5 constructed in accordance with the invention;

6 FIG. 4 is an electrical circuit diagram of a controller
7 for the motor of FIG. 3;

8 FIG. 5 is a generalized graph illustrating the
9 relationship of speed versus torque of a motor constructed
10 in accordance with the invention;

11 FIG. 6A is a diagram of square wave power available
12 from an inverter illustrated in FIG. 7;

13 FIG. 6B is a diagram of a modified square wave power
14 signal produced by the circuit of FIG. 7;

15 FIG. 7 is a circuit diagram for controlling the speed
16 of the motor of FIG. 3;

17 FIGS. 8A through 8D are diagrammatic representations of
18 signals developed in the circuit of FIG. 7;

19 FIG. 9 is a diagrammatic illustration of a system for
20 controlling the speed of a motor constructed in accordance
21 with the invention;

22 FIG. 10 is a schematic illustration of a motor arranged
23 for speed control by the control system of FIG. 9;

24 FIG. 11 is an alternative circuit for driving the motor
25 of FIG. 3;

26 FIG. 12 is a schematic representation of a motor of the
27 invention having field windings arranged in quadrature;

28 FIG. 13 is a circuit for driving the motor of FIG. 12;

29 FIG. 14 is a schematic perspective view of a four pole
30 three-phase motor constructed in accordance with the
31 invention; and

1 FIG. 15 is a diagrammatic illustration of the field
2 vectors of one of the windings of the motor of FIG. 14.

3 DESCRIPTION OF THE PREFERRED EMBODIMENTS

4 Referring now to FIG. 1, a motor 10 has a stator 11
5 with a field winding 12 and a rotor or armature 14 supported
6 by suitable bearing structure for rotation about an axis 16.
7 The winding 12 is arranged in two sections or portions 12a,
8 12b on diametrically opposite sides of the rotor 14. The
9 rotor 14 has a conductive loop 17 that has two diametrically
10 opposite portions 18 near the periphery of the rotor that
11 extend parallel to the rotor axis 16 and two end portions
12 19. A main body 21 of the rotor 14 can be constructed of
13 suitable magnetic silicon steel laminations in a manner
14 known in the art. The two loop portions 18 that extend
15 longitudinally of the rotor lie in a common plane that
16 passes through the rotor axis 16. For purposes of this
17 disclosure, the plane of the conductive loop 17 is taken as
18 the plane of the conductor portions 18. The conductive loop
19 17, which can be made of copper or aluminum, for example, is
20 electrically continuous; the end portions 19 shunt the
21 longitudinal portions 18. The stator 11 has its field
22 windings 12a, 12b wound about suitable magnetic material
23 such as a stack of magnetic silicon steel laminations 22a
24 and b.

25 When the field coil or winding 12 is energized with an
26 AC voltage, a magnetic field is created with a vector that
27 is parallel to an axis 23 extending between the windings
28 12a, b. With the field coil 12 thus energized with an AC
29 voltage, when the rotor 14 is displaced from the illustrated
30 solid line position through an angle ψ magnetic field
31 conditions urge the rotor 14 to return to the solid line

1 position where the plane of the conductive loop 17 is
2 aligned with the field axis 23. That is, the magnetic field
3 conditions urge the rotor 14 to the position where the angle
4 ψ is 0.

5 FIG. 2 is a generalized diagram of the relationship
6 between torque and angular displacement ψ . The diagram
7 shows that the torque tending to move the rotor 14 towards
8 the position of alignment with the axis 23 increases
9 proportionately with the displacement or angle ψ . Torque
10 reaches a maximum value at about 70° ; at displacements
11 beyond this, the torque diminishes. At ψ equal to 90° , i.e.
12 when the plane of the conductive loop 17 is transverse to
13 the direction of the field vector of the winding 12, the
14 torque reduces to 0. This $\psi = 90^\circ$ position can be called a
15 hard neutral while the position at ψ equal to 0 can be
16 called a soft neutral.

17 When the plane of the conductive loop 17 is turned from
18 alignment with the field vector of the stator 11, i.e. ψ not
19 equal to 0, the AC magnetic field produced by the winding 12
20 induces an AC current in the conductive loop 17. This rotor
21 current produces its own magnetic field which opposes the
22 stator field. The opposing field produced by the conductive
23 loop 17 increases the reluctance of the flux path of the
24 stator field. It can be shown that in an electromechanical
25 system, such as the motor 10 illustrated in FIG. 1, physical
26 laws work to reduce the reluctance in the system.
27 Consequently, the motor 10 behaves as discussed with the
28 rotor 14 being urged to a position where the plane of the
29 conductive loop 17 is aligned with the axes 23 and the
30 reluctance of the motor system being reduced.

31 The motor 10 of FIG. 1, as so far described, is not
32 practical as a general purpose rotating motor since it

1 cannot sustain continuous rotation of the rotor. However,
2 the motor's characteristics, as described, are helpful in
3 understanding the operation of other motors, constructed in
4 accordance with the invention, such as those described
5 hereinbelow.

6 FIG. 3 diagrammatically shows a motor 26 that applies
7 the foregoing principles in a two pole rotor 14, like that
8 described with reference to FIG. 1, but with a three phase
9 stator 28. (The "two pole" designation pertains to the
10 rotor or armature and derives from north and south magnetic
11 poles produced by the conductive loop 17 when the loop is in
12 an AC magnetic field.) The stator 28 typically includes a
13 body formed by a stack of laminations of suitable magnetic
14 silicon steel with internal axially oriented slots 30
15 distributed about the periphery of the rotor 14 as is
16 generally conventional in motor construction. A winding A
17 has turns wrapped axially around the rotor. The turns
18 include longitudinal or axially oriented portions disposed
19 in the lamination slots 30 on diametrically opposite sides
20 of the rotor 14 and end portions circumferentially looped
21 around the axial projection of the rotor in a manner known
22 in the motor art. The longitudinal portions of the turns of
23 the winding A are geometrically centered on a plane
24 represented at 31 that passes through the rotor axis 16.
25 For clarity, only the winding A is illustrated in FIG. 3 and
26 it will be understood that the other windings B and C are
27 similar in construction. The planes of the windings A, B
28 and C are oriented at 120° relative to one another with
29 reference to the axis 14 of rotation of the rotor 14 and
30 pass through this axis so that adjacent portions of the
31 windings A, B and C are centered at 60° intervals. The
32 winding A, when energized with AC power develops an AC

1 magnetic field vector 32 in a plane 33 perpendicular to the
2 plane 31 of the winding A. The other windings B, C,
3 similarly, produce AC magnetic field vectors perpendicular
4 to their respective planes. The windings A, B and C are
5 thus in a physical or mechanical phase relationship to one
6 another and are electrically isolated from one another. By
7 switching or modulating AC power sequentially to the
8 mechanically phased windings A, B and C, the rotor 14 will
9 be driven in rotation. As explained hereinabove, the rotor
10 14 will tend to align itself with the field vector of an
11 energized winding (or as discussed later the resultant field
12 vector of simultaneously energized field windings). When
13 the plane of the rotor conductive loop 17 approaches the
14 vector of the field from one energized winding, that winding
15 is de-energized while the adjacent winding in the direction
16 of rotor rotation is energized. By continuing this field
17 switching process, the rotor 14 is caused to rotate
18 continuously.

19 FIG. 4 illustrates an example of a circuit or
20 controller 36 suitable for driving the two pole, three
21 winding phase motor 26 of FIG. 3. The motor windings are
22 represented as A, B and C in the circuit of FIG. 4. In the
23 circuit, commercial power, e.g. 60 Hz, 110 volt, single
24 phase power is connected to lines 37, 38. This power is
25 converted to DC in a rectifier and voltage doubler circuit
26 comprising a pair of diodes 39, 41 and capacitors 42, 43.
27 Positive and negative voltages are developed on respective
28 lines or busses 46, 47.

29 Square wave AC power is supplied independently to each
30 winding A, B or C from paired power mosfet switches 51, 52
31 associated with each winding. One of the mosfet switches 51
32 supplies positive voltage while the other 52 supplies

1 negative voltage thereby producing an AC power signal. The
2 mosfet switches 51, 52 are driven by an associated
3 integrated circuit 53 (such as an IR 2104). These drivers
4 53 are powered by a suitable 12 volt DC source. Each driver
5 53 alternately operates the associated mosfets 51, 52 at a
6 frequency imposed by a frequency generator 54 (such as an
7 MCI 4046) signalling from its output (pin 4) to an input
8 (pin 2) of each driver 53. The frequency can be any
9 suitable frequency, preferably higher than commercial power
10 of 60 or 50 Hz. A typical frequency can be between 100 to
11 250 Hz but can be higher if design parameters require such
12 and appropriate materials are used.

13 A shaft encoder 56 (FIG. 3) of any suitable type and
14 preferably a non-contact type monitors the angular position
15 of the rotor 27 and, therefore, the plane of the conductive
16 loop 17. In the illustrated example of FIG. 3, the shaft
17 encoder 56 senses when a 60° arc on a drum rotating with the
18 rotor 14 associated with each winding A, B or C passes the
19 reference point of a non-rotating part 59 of the encoder
20 fixed relative to the stator 28. The drum 57 of the encoder
21 56 is divided into three channels, each channel
22 corresponding to one of the field windings A, B or C. The
23 encoder 56 signals the driver 53 of a particular field
24 winding A, B or C when an angular sector on the drum 57
25 associated with that particular winding is in proximity to
26 the non-rotating part 59 of the encoder. The encoder 56
27 maintains the signal to the appropriate driver 53 for a time
28 in which a field winding A, B or C develops a relatively
29 large torque on the rotor. This period will be, roughly
30 when the plane of the conductive loop 17 is between 75 and
31 15° out of alignment with the magnetic field vector of a
32 particular winding (i.e. $75^\circ \geq \psi \geq 15^\circ$).

1 The time period or, more properly, the angular duration
2 of energization of a particular field A, B or C can be set
3 by the geometry of the codes on the drum 57 of the encoder
4 56. The drum 57 may be encoded with arcs of detectable
5 material that have a dwell of 60°. This geometry allows
6 each winding, where there are three windings, to be
7 energized twice for each revolution of the rotor 14. While
8 a driver 53 is enabled (i.e. turned on) from a channel of
9 the encoder 56, the driver cycles the associated mosfet
10 switches 51, 52 on and off at the frequency produced by the
11 frequency generator 54. The mosfet switches 51, 52 thereby
12 apply a square wave AC power signal, at the frequency of the
13 generator 54, to the associated field winding A, B or C.
14 With the circuit of FIG. 4 when one of the windings A, B or
15 C is energized the other two windings are inactive.

16 The motor 26 of FIG. 3, driven by the open loop circuit
17 36 of FIG. 4 has a desirable speed torque curve
18 schematically illustrated in FIG. 5. It will be seen that
19 the motor 26 approaches a constant horsepower device.
20 Additionally, the motor 26 is characterized by relatively
21 high starting torque and is capable of relatively high speed
22 operation. A motor operating with the principles of the
23 motor 26 discussed in connection with FIGS. 3 and 4 can be
24 constructed with more field windings or field phases. The
25 windings, typically, can be evenly spaced around the stator
26 and suitable corresponding additional driver circuits and a
27 modified shaft encoder can be employed. Such a motor has
28 the advantage of less torque ripple than that of the
29 illustrated three phase motor 26.

30 The speed of the motor 26 and like motors can be
31 controlled by either controlling the power delivered to the
32 motor or by controlling the position of the shaft encoder

1 signals relative to the stator. Each method can have many
2 variations. Controlling the power to the motor may be
3 implemented very simply, but such control may not
4 necessarily produce the best efficiency over a wide speed
5 range. Controlling the relative positions of the encoder
6 signals may produce better efficiency, but may be more
7 complex in circuit implementation for certain applications.
8 In some applications, a combination of both methods may be
9 useful.

10 One way of controlling power for speed control is to
11 control the width of each 1/2 cycle of a voltage square wave
12 delivered to the motor. Full power of the square wave is
13 applied when each half cycle occupies the total time of one
14 half period as depicted in FIG. 6A. If the beginning of
15 each half cycle is delayed by some fraction of the half
16 period, as depicted in FIG. 6B, then the total amount of
17 power delivered to the motor is reduced. The motor is not
18 sensitive to waveform (does not need sine waves) so that
19 only the total energy per half cycle is significant. There
20 are many ways to implement this kind of control; a simple
21 version is shown in FIG. 7. This circuit is used in
22 conjunction with the circuit of FIG. 4. The frequency
23 generator 54 is redrawn here. As will be understood from
24 the following discussion, the circuit of FIG. 7 is
25 interposed in the lines from the encoder 56 to the drives 53
26 for the field windings A, B and C. The frequency signal
27 output of the frequency generator 54 is fed into pin 2 of IC
28 12 which is a four stage binary counter. Each stage divides
29 the frequency by 2. At pin 6 of IC 12 (the output of the
30 4th stage), the frequency is 1/16 of the input at pin 2.
31 The output frequency at pin 6 is fed into the driver stages
32 53 (at pin 2) of each power mosfet switch 51, 52 (FIG. 4)

1 that delivers power to a particular stator winding phase or
2 coil A, B or C. In this arrangement, the frequency
3 generator 54 is typically set to a frequency that is 16
4 times greater than what is used in the original circuit in
5 FIG. 4. The binary outputs from the other three stages are
6 connected to a summing resistor network 61 at the input of
7 an operational amplifier designated as IC 13 at pin 2. The
8 output signal at pin 1 of IC 13 will appear as a sawtooth
9 waveform and will be related to the square wave output on
10 pin 6 of IC 12 as shown in FIGS. 8A and 8B, respectively.

11 A speed command signal and a speed feedback signal
12 (e.g. derived from the shaft encoder) are summed
13 algebraically at pin 9 of IC 13 and the difference (speed
14 error signal) is produced at pin 8 of IC 13. At pin 14 of
15 IC 13 is the polarity inversion of the error signal. The
16 error signal is then compared with the sawtooth waveform by
17 the comparator circuit composed of pins 6, 5 and 7 of IC 13.
18 With reference to FIG. 8C, when the magnitude of the error
19 signal is below the sawtooth level, the output of pin 7 is
20 0; when the magnitude of the error signal is above the
21 sawtooth level, the output of pin 7 is positive (a logic
22 "1"). This output signal modulates the encoder signals that
23 feed into the power mosfet drivers 53. In essence, the
24 signal controls the turn on of each driver 53 at its pin 3.
25 This is accomplished by dual input "and" gates shown as IC
26 14 (MC 14081B). Signals from the encoder 56 feed into one
27 gate input and the signal from pin 7 of IC 13 feeds into the
28 second gate input. The output of each gate IC 14 then feeds
29 into the pin 3 of a respective driver 53. The result is a
30 power signal applied to the motor field windings A, B or C
31 as shown in FIG. 6D. As the speed error signal varies in
32 magnitude, the width of each half cycle will vary in

1 accordance. Where the power is supplied as a sine wave,
2 such as from commercial power, a speed control circuit can
3 be arranged to eliminate the beginning of each half cycle,
4 typically in the manner an SCR is regularly used in like
5 service.

6 The second method that can be used for speed control is
7 to shift the encoder signals to different phase or winding
8 drivers in accordance to the magnitude of the speed error
9 signal. FIG. 9 illustrates circuitry to accomplish this.
10 The select signal is derived from the speed control error
11 signal.

12 A motor 62 schematically shown in FIG. 10 has eight
13 field windings (a - h) and, accordingly, eight driver
14 circuits (corresponding to elements 53, 51 and 52 in FIG.
15 4). The field windings a - h are like the windings A, B and
16 C in FIG. 3. If a shaft position encoder or sensor 63 has
17 its signals directed to turn on the field coils which
18 produce the maximum torque, then the motor speed will
19 increase to the point where the load torque is equal to the
20 produced or developed motor torque. To reduce the torque
21 and lower the speed, it is necessary to direct the signals
22 of the position encoder 63 to different field coils. Speed
23 control can thus be obtained by switching the encoder
24 signals to different coils in response to the speed control
25 error signal. The plane of the armature conductive loop 17
26 is shown in relationship to the field coil position labelled
27 a - h. If coil a is energized, maximum torque is generated
28 in the counter-clockwise direction. A magnetic field vector
29 64 of winding a is perpendicular to the plane of winding a.
30 If field coil b were energized, a lesser torque would be
31 created, and if field coil c were energized, an even lesser
32 torque would be developed. By shifting the encoder

connection to energize different coils, the torque is controlled. By using the speed error signal to determine the switching, the motor speed can be regulated. The speed error signal magnitude is compared to fixed signal voltage levels that are stepped by fixed increments. When the speed error exceeds each fixed level, a new connection arrangement is made between the encoder and the field coils. For example, with eight field coils, suppose that at the maximum level, encoder output A controls coil a and encoder B controls coil b, etc. Then, when the error signal drops to the next level, a logic switching action takes place in a multiplex gate 63 (FIG. 9) to connect encoder output A to coil b, and encoder output B to coil c, encoder C to coil d, etc. Then, when the error signal drops to the next level down (third level), the logic switching action connects encoder output A to coil c, and encoder output B to coil d, encoder output C to coil e, etc. Thus, the control acts to shift the position of the encoder signals in proportion to the magnitude of the error signal. This action will then increase or decrease torque and, accordingly, increase or decrease speed.

FIG. 11 shows an alternative controller or circuit 70, of simplified design, for operating the motor 26. Single phase alternating current power such as 110 volt 60 Hz commercial power is supplied to the windings A, B and C through corresponding triacs 71 or other electrically controllable switches. A frequency generator 73, (MCI 4046) produces a series of pulses having a frequency that is proportional to the voltage set by a potentiometer 72. The pulses are input to a counter 74 such as a CMOS 4017. The three outputs of the counter 74 are applied to sequentially fire the triacs 71 through a buffer 76 such as a CMOS 4049

1 inverting buffer that feeds the opto isolator trigger to
2 each triac. The counter 74 assures that the windings or
3 phases A, B and C are triggered sequentially at a rate
4 corresponding to the frequency set by the voltage at the
5 potentiometer 72. The motor 26, when operated by the
6 circuit of FIG. 11, will run at a speed synchronous with the
7 rate that the field windings A, B and C are triggered. The
8 circuit 70 with the adjustable potentiometer 72 and variable
9 frequency of the generator 73 thus provides a simple method
10 of speed control for the motor 26. As this circuit 70 of
11 FIG. 11 suggests, the motor 26 and others constructed like
12 it in accordance with the invention can be operated directly
13 off a commercial single phase power supply such as, for
14 example, 120 volt 60Hz power where high speed operation is
15 not required. Conversely, this motor 26 and the circuit 70
16 can be supplied with a higher frequency power supply where
17 it is desired to operate the motor at higher speeds.
18 Innumerable other control systems and circuits are suitable
19 for operating a motor constructed in accordance with the
20 invention as will be apparent from an understanding of the
21 present disclosure.

22 A flux vector drive is also contemplated for the motor
23 of the invention. Referring to FIG. 12, a simple field
24 winding configuration for a two winding two pole motor 80 is
25 shown. Stator field or phase windings X, Y are physically
26 located in quadrature and labelled X and Y to correspond
27 with x and y axes. The windings X, Y create magnetic flux
28 vectors along the corresponding x and y axes. Currents
29 flowing through both sets of windings X and Y create a
30 magnetic field flux vector 81 which is the vector sum of the
31 individual magnetic flux vectors created by the currents in
32 the separate windings X, Y. A vector angle θ of the vector

1 varies with respect to the X axis depending on respective
 2 magnitudes of the currents in windings X, Y.

3 The magnitudes of the AC currents in the windings X, Y
 4 are:

5 $I_x = \cos\theta \sin 2\pi f_c t$; and

6 $I_y = \sin\theta \sin 2\pi f_c t$;

7 where f_c is the frequency of the current supplied, such as
 8 60 Hz. The field flux vector 81 represents an alternating
 9 magnetic field with the frequency f_c . The field flux vector
 10 81 can be positioned at any angle θ by varying the currents
 11 in the field windings X, Y according to the following
 12 relationship:

13
$$\theta = \sin^{-1} \left(\frac{I_y}{\sqrt{I_x^2 + I_y^2}} \right)$$

14 The motor 80 has a rotor 14 like that described in
 15 connection with FIG. 1; the plane of the conductive loop 17
 16 is displaced from the X axis by a rotor angle ϕ . The rotor
 17 14 rotates synchronously at the speed that the field vector
 18 81 is rotated. As discussed below, the field windings can
 19 be supplied with modulated AC currents from power amplifiers
 20 operated by a signal processor to appropriately rotate the
 21 magnetic field vector 81.

22 By creating and controlling a difference between the
 23 field flux vector angle θ and the rotor angle ϕ , the torque
 24 output of the motor 80 can be controlled. That is, the
 25 torque is controlled by controlling the relative positions
 26 of the field flux vector and the plane of the conductive
 27 loop 17 on the rotor 14. As discussed previously with
 28 reference to FIG. 2, torque is developed when the rotor or
 29 armature 14 is located where there is an angular deflection
 30 ψ between the plane of the conductive loop 17 and the flux

1 vector between the winding portions 12a, b; this torque
 2 varies with the magnitude of the angle ψ . Similarly, in
 3 FIG. 12, the torque varies with the difference between the
 4 flux vector angle θ and the rotor angle ϕ . Note the
 5 relationship $\psi = \theta - \phi$.

6 As previously discussed, the vector angle θ is varied
 7 by varying the current amplitudes in the field windings X,
 8 Y. Since the currents are AC, the field currents will be
 9 suppressed carrier amplitude modulated sine waves that can
 10 be represented as:

11 $I_x = \cos(\omega_R t + \psi) \sin 2\pi f_c t$; and

12 $I_y = \sin(\omega_R t + \psi) \sin 2\pi f_c t$;

13 where ω_R is the rotational speed of the rotor 14. The
 14 angular deflection ψ with respect to the field flux vector
 15 is determined by the respective field currents I_x , I_y and
 16 the angular velocity ω_R :

17 $\pm\psi = \sin^{-1} \left(\frac{I_y}{\sqrt{I_x^2 + I_y^2}} \right) - \omega_R t$

20 Referencing FIG. 2, the deflection angle ψ is varied to
 21 achieve the desired torque characteristics by varying the
 22 currents I_x , I_y . The rotor position ϕ is sensed, for
 23 example, by a transducer or electrical parameters. Rotor
 24 position information is used to control the flux vector
 25 position θ to maintain the desired deflection ψ and,
 26 therefore, the motor torque.

27 A flux vector control circuit 85 that applies the
 28 foregoing principles and relationships of field current,
 29 field vector and rotor angle for torque control is shown in
 30 FIG. 13. The control 85 includes a signal processor 86 with
 31 two outputs for generating the currents I_x , I_y . The
 32 currents are fed through respective power amplifiers 87 to

the field windings X, Y. Frequency F_c is set by a suitable frequency input. A rotor position sensor 89, such as a numerical shaft position sensor, provides rotor position information data to the signal processor 86. A torque command input, corresponding to a deflection angle ψ is provided to the signal processor to control torque. The signal processor 86 in accordance with the foregoing formulas generates the currents I_x , I_y as functions of the frequency F_c , rotor position ϕ (which indicates rotor speed ω_R), and torque command deflection angle ψ to control the torque characteristics of the motor 80. The speed of the motor is controlled according to the rate ω at which the carrier signal is modulated, which can be selected by a speed input. The rotor position sensor can be connected to provide speed or position feedback, diagrammatically represented at 88, through a torque control 84 to control the torque command angle setting ψ .

A motor constructed in accordance with the invention can be made with four poles as schematically shown in FIG. 14. The motor 90 can develop twice the torque of a similarly sized two pole motor such as the motor 26 in FIG. 3. The illustrated motor 90 has three field winding phases designated Phase A, Phase B and Phase C. Each Phase A, B and C has ^{four} ~~four~~ coils 91, 92, 93, and 94. Each of these coils has a pair of spaced axially extending portions 96 and a pair of end turn portions 97, one at each end of a stator typically of suitable laminations represented by the circular line 98. The coils 91, 92, 93 and 94 are connected in series with alternate coils wound in a clockwise direction and intervening coils wound in counter-clockwise direction. Alternatively, the coils 91 - 94 can be connected in parallel. For clarity, the coils 91 - 94 of

1 only one phase (A) is shown, it being understood that the
2 other phases B and C are identical. A rotor 99 of the motor
3 90 has four conductive wires or rods 100 equally spaced
4 around the circumference of the rotor 99 and extending
5 longitudinally of the rotor. The conductors 100 are
6 interconnected or shunted by end wires or conductors 101 at
7 each end of each conductor 100. The longitudinal conductors
8 100, like the conductors 17 of the rotor 14 of FIG. 3, are
9 parallel with the axis of rotation of the rotor 99 on a
10 shaft 95. The rotor 99 and stator 98 typically include
11 bodies formed of silicon steel laminations as previously
12 described. The windings of Phases A, B and C can be
13 energized by a circuit like that shown in FIGS. 4 or 11.
14 Motors having a greater even number of poles such as 6, 8 or
15 more, can be constructed similarly to the four pole motor of
16 FIG. 14 and such motors will have a proportionately higher
17 torque capacity.

18 As will be understood from the foregoing disclosure,
19 the motor of the invention can take various forms and can be
20 powered by innumerable electrical circuit arrangements, both
21 open and closed loop. Switches for the field windings can
22 include triacs, transistors, silicon controlled rectifiers
23 (SCR's) and magnetic amplifiers, for example. The rotor,
24 rather than having a conductive loop to present a variable
25 reluctance to the stator field, can be formed with a
26 diametrically disposed air gap or a conductive plate in the
27 plane otherwise occupied by the conductive rotor loop. The
28 rotor can be disposed around, rather than in, the stator.
29 The conductive loop or loops on the rotor can be skewed in a
30 helical or like sense to reduce torque ripple. The number
31 of field windings and related electronic switches, also, can
32 be increased to decrease torque ripple. Some of the turns

1 of a particular winding can share the same stator lamination
2 slot or angular position as some of the winding turns of an
3 adjacent winding.

4 The motor can be supplied with a shaft encoder and
5 appropriate circuitry for operation as a stepping motor and
6 is especially suitable for large size stepping motors. A
7 desired angular resolution for a stepping motor application
8 can be achieved by providing a suitable number of field
9 windings. As previously discussed herein, the rotor will
10 seek to align the plane of the conductive loop, or
11 equivalent structure, to the magnetic field vector of a
12 particular winding that is energized. The motor is
13 reversible simply by reversing the sequence that the field
14 windings are energized by the related circuitry.

15 A circuit powering the field windings of the motor can
16 energize more than one field winding at a time to reduce
17 torque ripple and/or the circuit can be arranged to modulate
18 power to the windings rather than simply turning them on and
19 off. Field windings on the stator can have various
20 configurations besides those illustrated in FIGS. 1, 3 and
21 14, it being important that the winding arrangement be
22 capable of producing an AC magnetic field in the space of
23 the rotor that moves around the axis of the rotor.

24 While the invention has been shown and described with
25 respect to particular embodiments thereof, this is for the
26 purpose of illustration rather than limitation, and other
27 variations and modifications of the specific embodiments
28 herein shown and described will be apparent to those skilled
29 in the art all within the intended spirit and scope of the
30 invention. Accordingly, the patent is not to be limited in
31 scope and effect to the specific embodiments herein shown
32 and described nor in any other way that is inconsistent with

- 1 the extent to which the progress in the art has been advanced by the invention.
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